A New Device to Study Isoload Eccentric Exercise

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Abstract

Guilhem, G, Cornu, C, Nordez, A, and Guével, A. A new device to study isoload eccentric exercise. *J Strength Cond Res* 24(X): 000–000, 2010—This study was designed to develop a new device allowing mechanical analysis of eccentric exercise against a constant load, with a view in mind to compare isoload (IL) and isokinetic (IK) eccentric exercises. A plate-loaded resistance training device was integrated to an IK dynamometer, to perform the acquisition of mechanical parameters (i.e., external torque, angular velocity). To determine the muscular torque produced by the subject, load torque was experimentally measured (T_{Lexp}) at 11 different loads from 30° to 90° angle (0° = lever arm in horizontal position). T_{Lexp} was modeled to take friction effect and torque variations into account. Validity of modeled load torque (T_{Lmod}) was tested by determining the root mean square (RMS) error, bias, and 2*SD* between the descending part of T_{Lexp} (from 30° to 90°) and T_{Lmod}. Validity of T_{Lexp} was tested by a linear regression and a Passing–Bablok regression. A pilot analysis on 10 subjects was performed to determine the contribution of the torque because of the moment of inertia to the amount of external work (W). Results showed the validity of T_{Lmod} (bias = 0%; RMS error = 0.51%) and T_{Lexp} *SEM* = 4.1 N·m; Intraclass correlation coefficient (ICC) = 1.00; slope = 0.99; *y*-intercept = −0.13). External work calculation showed a satisfactory reproducibility (*SEM* = 38.3 J; ICC = 0.98) and moment of inertia contribution to W showed a low value (3.2 ± 2.0%). Results allow us to validate the new device developed in this study. Such a device could be used in future work to study IL eccentric exercise and to compare the effect of IL and IK eccentric exercises in standardized conditions.

Key Words constant load, lengthening contraction, ergometer, knee extensors, muscular torque

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Introduction

Eccentric exercise involves muscular contractions against a load higher than the torque exerted by the activated muscular group. The mechanical load applied to the mobilized segment during eccentric exercise involves stretching of elastic components of muscle–tendon complex that absorbs mechanical energy. This energy is dissipated as heat or stored as elastic recoil potential energy, and that can subsequently be recovered. Such a mechanical behavior leads to the production of high muscular force levels that can induce some muscular damages (25). To protect the contractile structures against these high tension levels, the neuromuscular system uses neural regulatory mechanisms at the spinal level (e.g., presynaptic inhibition of group Ia muscle spindle afferents, homosynaptic postactivation depression [13]) that limits the recruitment or discharge rate of motor units (14). These mechanical and neural specific responses to eccentric exercise led some authors to study its effects in rehabilitation protocols to restore neuromuscular function (11) or in training sessions to improve the muscular force production (24).

Eccentric exercise is often performed against a constant external resistance (isoload, IL) (8,19). During such a task, movement velocity is variable, and the muscles are mainly loaded at flexed and extended joint angles. Although the terms IL or isoinertial actions more accurately reflect weight loading actions (2,8), these kinds of tasks are often termed isotonic movements in the literature (15). Eccentric exercises can also be performed at a constant velocity (23) on an isokinetic (IK) dynamometer. In IK movements, subjects have to overcome an accommodating resistance adapted to the muscle torque subjects are able to exert, thus leading to a constant movement velocity. Isokinetic mode is consequently supposed to maximally load the muscles through the overall range of motion and to produce of higher peak torque than the IL mode. These differences in torque and movement velocity may induce different responses and adaptations of the neuromuscular and musculoskeletal systems. Numerous studies have investigated the effect of IK (16,18,24) or IL (19,29,36) eccentric training on the neuromuscular system, without comparing the specific adaptations induced by these 2 eccentric exercise modes. Isoload eccentric exercise is performed on plate-loaded resistance training devices or with weightlifting bars and dumbbells, whereas IK eccentric

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exercise is realized on IK dynamometers. Considering the lack of standardization of mechanical parameters (e.g., movement velocity, amount of external work), comparison of these 2 exercise modes is consequently difficult to complete. Previous studies conducted on concentric exercise showed that mechanical differences in mechanical load in the IL and IK modes could induce some specific neural responses (30,32,33). Thus, it could be interesting to characterize the response of neuromuscular system to IL and IK eccentric exercises in standardized conditions. Such a study requires a device allowing acquisition of mechanical parameters in both modes to develop a standardization methodology of the amount of external work and the angular velocity (31).

Isokinetic dynamometers (e.g., Biodex, Shirley, NY, USA; Cybex, Medway, MA, USA; Kin-Com, Chattanooga, TN, USA) do not allow performing eccentric exercise in IL mode. Therefore, we customized an IK dynamometer to perform acquisition of mechanical parameters such as muscular torque, joint angle, and angular velocity during IL eccentric exercise. This device was designed to measure the amount of external work performed and the angular velocity on the whole range of motion during both IL and IK exercise modes using the same ergometer. The aim of the present study was to test the validity of mechanical measurements performed by this customized device.

Methods

Experimental Approach to the Problem

The aim of this study was to develop a simple device to study eccentric exercise in the IL mode on the same ergometer that is commonly used in the IK mode. For this purpose, we added a system of guided loads to an IK dynamometer Biodex System 3 Pro (Biodex® Medical Systems, Shirley, NY, USA) to elicit the conditions of weightlifting (IL) exercise. This device was used to elicit lengthening contractions of knee extensor muscles against a constant load and measure the amount of external work and angular velocity in this exercise mode. External work (W) is calculated as the area under the muscular torque–angle relationship. In the IK mode, muscular torque is directly measured by the dynamometer. In the IL mode, the muscular torque exerted during eccentric contractions is produced against a load torque. Consequently, the torque measured by the dynamometer in the present study required a mathematical correction. Each torque applied on the dynamometer attachment was determined to calculate the muscular torque produced during eccentric exercise. This device was validated by the determination of accuracy and reproducibility of external work calculation.

Subjects

Ten male sport sciences students (age = 21 ± 3 years; height = 180 ± 6 cm; and body mass = 78 ± 9 kg) volunteered to participate in this study. All students were moderately active (daily sport activities = 1.4 ± 1.0 hours), nonspecific of a physical activity, and refrained from participating in a resistance training program for the duration of the study. Subjects were informed of risk and discomfort associated with the experimental procedures before they gave their written consent to participate. The study was approved by the local ethics committee and was conducted in accordance with the Declaration of Helsinki (1964 revised in 2001).

Procedures

Device Description. A specific module was integrated to the IK dynamometer to elicit IL eccentric exercise. This module was comprised by a plate-loaded resistance training device, a wire and a half-circle metal piece. The diameter of the half circle was equal to 0.395 m to be large enough for applying sufficient torque levels in eccentric exercise and small enough to be adjustable to the subjects with the smallest leg. Loads were anchored to the wire, which crossed 2 pulleys and followed the half-circle piece fixed to the lever arm, to maintain a constant applied torque on the whole range of motion (30–90°, 0° = lever arm in horizontal position) (Figure 1). In the return phase, the load was automatically pulled up by the motor of the dynamometer to the starting position (30°) at a constant angular velocity ($30°\cdot s^{-1}$) to ensure the subject performed eccentric-only exercise, without any intervention of the investigator or the subject during the return phase. Mechanical signals of the dynamometer (i.e., angle, torque and angular velocity) were recorded at a sampling frequency of 1,000 Hz.

External Work Calculation. Eccentric exercise produces negative work, involved in braking actions (i.e., jump landing, downhill running, and stairs descent) (12). The amount of external angular work (W) is calculated at each time interval

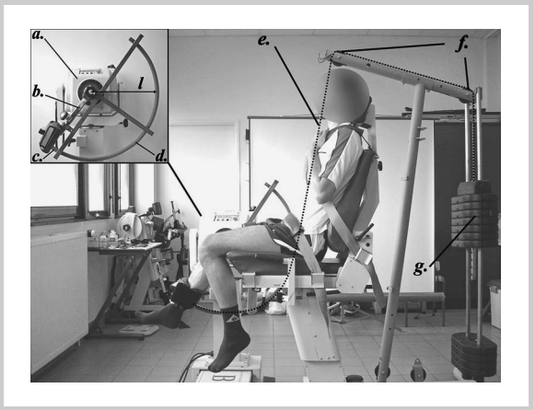

Figure 1. Picture of the device development. A plate-loaded resistance training device was integrated to an isokinetic dynamometer Biodex® System 3 (A). Loads (G) were linked to the dynamometer attachment by a wire (E). The wire passed through 2 pulleys (F) and followed a half-circle metal piece (D) fixed to the dynamometer attachment (B). a. Dynamometer–Biodex® System 3 Pro; b. dynamometer attachment. Half-circle metal piece and wire; c. fastening point of the wire on the half-circle metal piece; d. half-circle metal piece. l: diameter (0.395 m); e. wire. The way of the wire is indicated by the dashed line; f. pulleys; g. loads

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from the muscular torque produced by the subject (T_{mus}) and the angular position (θ), as expressed by equation 1:

$$W = \int_{\theta_0}^{\theta_n} T_{mus}\theta d\theta, \quad (1)$$

where W is the external work (J), T_{mus}, the muscular torque (N·m), and θ is the angle (rad).

Subjects produced a muscular torque (T_{mus}) in IL eccentric knee flexions opposing the load torque (T_L), the attachment torque (the lever arm and the half-circle piece, T_a), and the torque created by the subject's leg and foot combined (T_{leg}). Consequently, the determination of T_{mus} required the calculation of each one of the torques involved in IL eccentric exercise. According to the fundamental principle of dynamics, the torque balance existing on the dynamometer attachment in IL eccentric exercise is presented by equation 2:

$$T_{mus} = -T_{mes} + T_a + T_{leg} + T_L + J\ddot{\theta}, \quad (2)$$

where T_{mus} is the muscular torque (N·m); T_a, the attachment torque (N·m); T_{leg}, the leg torque (N·m); T_L, the load torque (N·m); J, the mass moment of inertia (kg·m^2); $\ddot{\theta}$, the angular acceleration of the lever arm (rad·s^{-2}); and T_{mes} is the measured torque (N·m).

To calculate T_{mus}, each component of equation 2 was determined. T_{mes} was directly measured by the dynamometer. T_a and T_{leg} were measured at a fixed knee angle (30°) and calculated on the whole range of motion (1). The methods used to assess T_L and $J\ddot{\theta}$ are described below.

Load Torque (T_L) Calculation. Eleven different loads (0 then 196–687 N, every 49 N) were applied on the lever arm without subject, from 30° to 90° with the dynamometer set in passive mode (angular velocity = 1°·s^{-1}) to measure the experimental load torque (T_{Lexp}) given by the dynamometer. Theoretically, the torque applied by the loads on the lever arm is calculated by equation 3:

$$T_{Lth} = mgl, \quad (3)$$

where T_{Lth} is the theoretical load torque (N·m); m, the load mass (kg); g is in m·s^{-2}; and l is the lever arm length(m).

Although experimental load torque measurements were close to the theoretical load torque, we identified (a) a friction effect and (b) variations of torque because of the imperfect rolling contact between the wire and the metal piece that exists on every plate-loaded resistance device, as illustrated in Figure 2. Consequently, equation 3 could not be used to accurately determine the torque applied by the load. Thus, descending phase (from 30° to 90° angle) of the T_{Lexp}–angle–load 3-dimensional relationship was modeled by a surface model as a T_{Lmod}–angle–load relationship (linear increase with torque and a second-degree polynomial model with angle, Figure 3) so that load–torque variations were taken into account. T_{Lexp} was also measured twice a week between the 2 measurements, to ensure there was no drift in the error value between T_{Lmod} and T_{Lexp}.

Mass Moment of Inertia Calculation. As shown by equation 2, the determination of T_{mus} requires the calculation of the torque because of the mass moment of inertia ($J\ddot{\theta}$). In IL eccentric exercise, the moment of inertia of the system (J) is calculated according to equation 4:

$$J = J_a + J_{leg} + J_L, \quad (4)$$

$$J_L = ml^2, \quad (5)$$

where J is the system moment of inertia (kg·m^2); J_a, the attachment moment of inertia (kg·m^2); J_{leg}, the leg moment

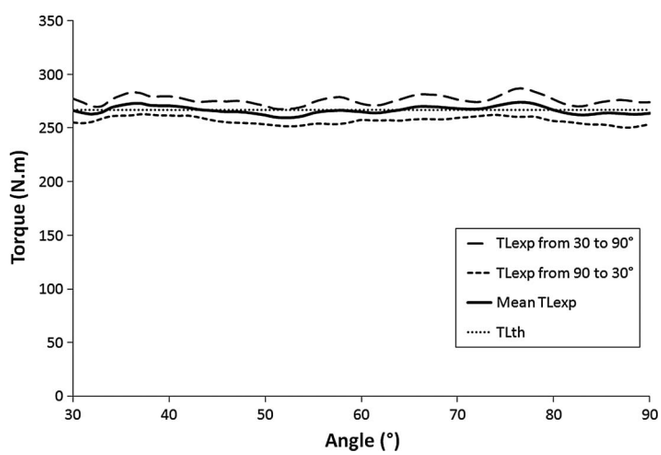

Figure 2. Typical result of the applied load torque measured without subject on the dynamometer, in passive condition (angular velocity = 1°·s^{-1}). A) The friction effect is shown by the different torque value in the descending phase of experimental load measurement (T_{Lexp} from 30° to 90°, long-dashed line) and the ascending phase of experimental load measurement (T_{Lexp} from 90° to 30°, short-dashed line). The thick line represents the mean of the 2 phases of T_{Lexp} measurement. B) Imperfections in rolling contact between the wire and the half-circle metal piece are shown by variations of T_{Lexp} on the whole range of motion.

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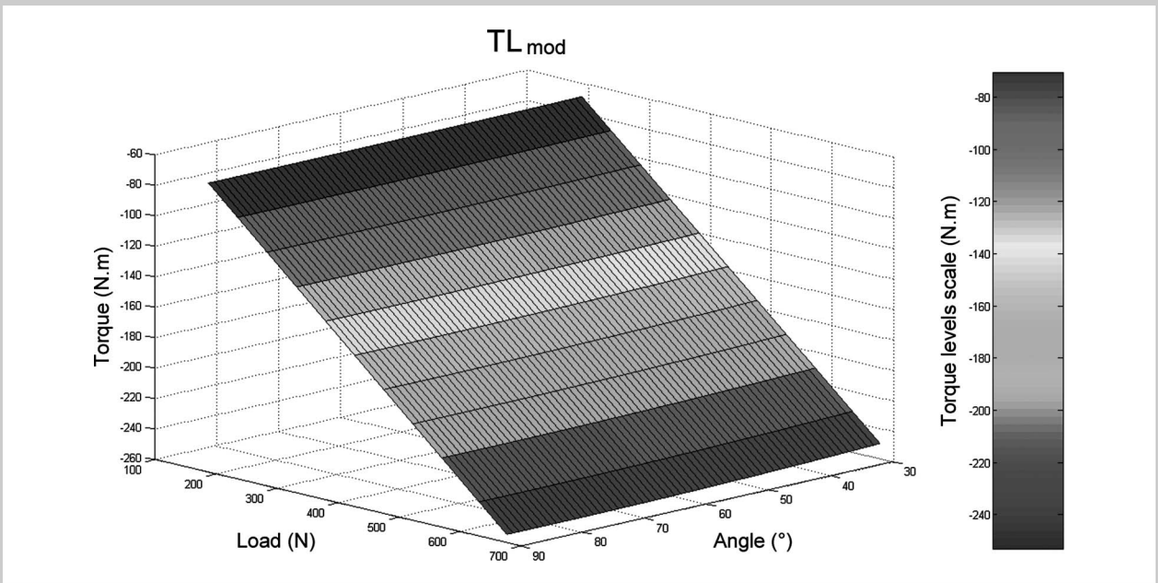

Figure 3. Graphical representation of the 3-dimensional relationship between modeled load torque (T_{Lmod}, N·m), the angle (°) and the applied load (N), on the overall range of motion (from 30° to 90°, 0° = lever arm in horizontal position). The colored-scale (on the right) indicates the level of load torque from the lowest values (blue color) to the highest values (red color).

of inertia (kg·m^2); J_L, the load moment of inertia (kg·m^2); m, the load mass (kg); and l is the radius of gyration (m).

A pilot analysis showed that the mean angular acceleration ($\ddot{\theta}$) in IL eccentric flexion was equal to 0.01 rad·s^{-2}, suggesting a low contribution of the torque because of the moment of inertia to the amount of external work. Therefore, we hypothesized that the contribution of J_{leg} and J_a could be considered as negligible. To estimate the maximal contribution of J_a and J_{leg} to the total moment of inertia, J_L was calculated, as the mass multiplied by the squared radius of gyration (0.395 m), for the lowest load used by the subjects (38 kg). Minimal value of J_L was equal to 5.929 kg·m^2. The segmental moment of inertia depends on the anthropometrical characteristics of the subjects. According to the table established by Zatsiorsky and Aktov (37), the mean segmental moment of inertia of a man's leg (J_{leg}) is about 0.369 kg·m^2, and J_a is estimated to 0.3 kg·m^2, resulting in a total contribution of J_{leg} and J_a about 0.669 kg·m^{-2}. Consequently, the maximal contribution of J_a and J_{leg} to J is estimated to about 10%.

To test the hypothesis that this low contribution (10%) can be considered as negligible, the moment of inertia contribution to the amount of external work was determined during an IL eccentric session. During a familiarization session, subjects get used to the customized dynamometer and their maximal repetition was determined (1RM). One repetition maximum corresponded to the maximal load that subjects were able to mobilize only one time on the whole range of motion (90–30°). One week later, subjects performed a test session consisting of a 5-minute warm-up on a cycloergometer, a specific warm-up on the dynamometer, and 1 set of 8 lengthening contractions of knee extensors of their dominant leg (the one used to kick a ball, all subjects were right-leg dominant) in the IL mode, at 120% of their 1RM. The amount of external work was calculated by the numerical integration of the T_{mus}–angle relationship (see *External work calculation*). Thereafter, the moment of inertia contribution to the amount of external work was determined. One week later, subjects

Table 1. Comparison between T_{lexp} and T_{Lmod}.*†

	Row value (N·m)	Relative value
Bias	0.0	0.0
RMS error	1.6	0.5
Max error	3.2	1.0
Min error	−3.5	−1.1
2*SD*	1.6	0.5

*RMS error = root mean square error; Max error = maximum error; Min error = minimum error; T_{Lexp} = experimental load torque; T_{Lmod} = modeled load torque.

†Bias, RMS error, Max error, Min error, and 2*SD*s between T_{Lexp} and T_{Lmod} expressed in row and relative value (as a percentage of mean).

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performed a second test session identical to the first test session previously described. The time interval between test sessions was chosen to ensure a complete strength recovery before the second test session (26).

Statistical Analyses

To determine the error between the load torque measurement and the modeled load torque (T_{Lmod}), Root mean square (RMS) error, bias, and 2 *SD*s between T_{Lexp} (from 30–90°) and T_{Lmod} were calculated for each applied load.

Validity of load torque measurement was determined by the calculation of the Bravais–Pearson correlation coefficient (r), slope and y-intercept of the linear regression, *SEM*, intraclass correlation coefficient (ICC), and coefficient of variation (CV) between T_{Lth} and T_{Lexp} (17). The power of this method to assess the validity of a measurement is discussed further in the literature (3,6,7). Thus, a Passing–Bablok regression (5) was also performed using Medcalc Software® (Mariakerke, Belgium). This method determines the slope and the y-intercept of linear regressions with a 95% confidence interval (95% CI). A significant difference between the 2 measurements is found if "1.0" for the slope and/or "0" for the y-intercept are not included in the 95% CI. As stated above, a friction effect was noticed during T_{Lexp} measurements (Figure 2). Consequently, to determine the validity of T_{Lexp}, a linear regression between the mean of the ascending phase (from 90° to 30°) and the descending phase (from 30° to 90°) of T_{Lexp}, and T_{Lth} was performed.

Trial-to-trial reproducibility of amount of external work between both identical test sessions was determined by the calculation of the ICC, *SEM*, and the CV (17). The critical level of significance was set at $p \leq 0.05$.

Results

Validity of Load Torque

The T_{Lmod}–load–angle 3-dimensional relationship is presented in Figure 3. Root mean square error, bias, and 2*SD* between T_{Lexp} and T_{Lmod} are presented in Table 1. Results showed the validity of T_{Lmod} with a bias equal to zero and an RMS error less than 1% of the mean of T_{Lexp} and T_{Lmod}.

Results concerning the validity of T_{Lexp} measurements showed satisfactory values of *SEM* (4.1 N·m), ICC (1.00), and CV (6.0%) between T_{Lexp} and T_{Lth} (34). Linear regression showed a y-intercept close to zero and a slope slightly lower than 1.00 (Figure 4). These results were confirmed by the Passing–Bablok regression that did not show any significant difference between the mean of T_{Lexp} and T_{Lth} (Figure 4).

Calculation of the Torque because of the Moment of Inertia

The mean contribution of the torque because of the moment of inertia reached 3.2 ± 2.0% (0.8–6.7%) of the total amount of work performed by the subjects in the IL eccentric set. Contribution of leg and attachment moment of inertia was about 10% of total moment of inertia. Leg and attachment moment of inertia contribution to the amount of external work was consequently less than 0.5%. Therefore, in

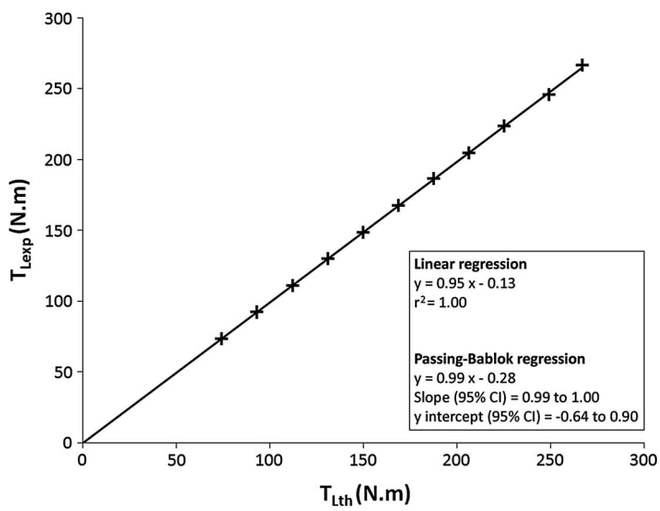

Figure 4. Validity of experimental load torque (T_{Lexp}) measurements in comparison of theoretical load torque (T_{Lth}), expressed by linear and Passing–Bablok regressions. T_{Lexp} was measured from 30° to 90° (0° = lever arm in horizontal position) without subject, at 11 different loads (0 then 196–687 N, every 49 N) with the dynamometer set in passive mode (angular velocity = $1°\cdot s^{-1}$). T_{Lth} corresponds to the theoretical torque applied by the load and was calculated by equation 3. Passing–Bablok regression showed no difference between the 2 values as shown by the 95% CI.

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accordance with our hypothesis (see *Mass moment of inertia calculation*), this contribution was considered as negligible.

Reproducibility of Work Calculation

Intraclass correlation coefficient and *SEM* values demonstrated a satisfactory reproducibility for the total amount of external work ($-1{,}777 \pm 272$ J vs. $-1{,}786 \pm 269$ J) performed by the subjects in the IL eccentric set during the 2 test sessions ($SEM = 38.3$ J; ICC = 0.98; CV = 2.3%).

Discussion

The aim of the present study was to test the validity of a simple new device allowing the acquisition of mechanical parameters during eccentric (or concentric) contractions against a constant external load. This device was developed on the same ergometer used in constant velocity movements, thus allowing the study of IL and IK movements in similar conditions. Reliability analyses showed satisfactory results which validated the mechanical measurements performed by this device.

Calculation of the amount of external work performed during IL eccentric exercise required the determination of the muscular torque produced by the subject. Consequently, each torque applied on the dynamometer attachment during eccentric exercise was determined (i.e., measured torque, load torque, leg torque, attachment torque, torque because of the mass moment of inertia). Experimental load torque measurements showed a friction effect. Nevertheless, the very low error between the experimental load torque and the theoretical load torque showed that this friction effect was considered by our methods. In addition, variations of torque because of the imperfect rolling contact between the wire and the metal piece were observed. Nevertheless, results showed that bias between experimental load torque and modeled load torque was equal to zero. Consequently, neither the friction effect nor the imperfect rolling contact between the wire and the half-circle metal piece had any effect on the external work calculation. Friction effect and imperfections of the material currently exist in weightlifting training conditions, thus increasing the interest of the use of this device with the goal of studying the effect of IL training.

Secondly, the mechanical load applied to the dynamometer attachment was almost perfectly constant and accurate, as demonstrated by the small SEM and CV, and the ICC value calculated between the experimental load torque and the theoretical load torque. These results were confirmed by the Passing–Bablok regression that showed no significant difference between the experimental load torque measurements and the theoretical load torque. The device developed in this study showed the validity of load torque measurements.

A major difference with IK movement is that angular velocity recorded in the IL mode is variable, thus implying changes in acceleration, notably at the start (extended knee angles) and the end (flexed knee angles) of the movement. Such mechanical characteristics could increase the contribution of the torque because of the moment of inertia to the total amount of external work performed in the IL mode. This contribution was consequently quantified and it reached less than 5% (3.2%). The calculation of amount of work did not take into account contribution of segmental moment of inertia of leg and attachment. However, the moment of inertia of leg and attachment was about 10% of the total moment of inertia, resulting in a contribution to the amount of external work less than 0.5%. Therefore, this result confirmed the hypothesis that J_{Leg} and J_a can be neglected to determine the amount of work. Calculation of external work based on muscular torque measurements showed a satisfactory reproducibility. Consequently, the validity and reproducibility analyses performed in passive and dynamic conditions support the validation of the simple device developed in the present study.

Study of IL eccentric exercise has previously been conducted to determine the level of muscular damages induced (10,15,20), the muscle activation patterns (28), or to characterize the mechanical properties of musculoskeletal system (27) during such exercise. Numerous studies attempted to determine specific force gains and physiological adaptations induced by an eccentric training in comparison to a concentric training period in the IL mode (22,35,36). None of these studies precisely evaluated mechanical load by the quantification of the amount of work performed and the angular velocity of movement. The present study allows the exact determination of this external load by the quantification of external work. This is a first step before determining specific effects of lengthening contractions in comparison of shortening contractions in IL mode in an acute session or after a training period.

Practical Applications

The device designed in this study allows the acquisition of mechanical parameters during eccentric exercise in IL mode on the same dynamometer used to usually perform eccentric contractions in the IK mode. This work enables the development of a standardization methodology of the IL and IK modes in eccentric contraction to compare their effects on the neuromuscular system. Such a study was previously tested in concentric exercise (31), showing differences in neural activation patterns in the IL and IK modes in shortening contractions as a function of angle (32). The mechanical differences that exist between the IL and IK modes in terms of torque and angular velocity suggest that specific structural and neural responses may likewise be observed in eccentric contractions (4,9,21,28).

This device also allows acquisition of mechanical parameters during eccentric (or in concentric) contractions against a constant load. Such a device allows the study of constant external resistance exercise rather than dynamometer-simulated isotonic exercise mode (30). Also, the movement is smoother and subjects have better control of their movement velocity. This device could be used to assess muscular force capacities (i.e., muscle strength, movement velocity, and muscle power as a function of joint angle) in eccentric contractions in the IL mode as commonly

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performed on an IK dynamometer. Furthermore, this device automatically pulls the load up to the starting position at a constant angular velocity. This technical aspect avoids any intervention of the investigator against heavy load levels (usually 100–140% of 1RM in eccentric training).

To conclude, we developed a simple device that enables the acquisition of mechanical parameters during IL eccentric exercise. This study allows the determination of mechanical load by quantification of muscular torque, angle, angular velocity, and external work on the same ergometer used in the IK mode. The calculation of external work considered factors such as friction, material, and moment of inertia effects that potentially exist in IL training conditions (e.g., weightlifting exercises). This dynamometer development could be useful in future studies to develop a standardization methodology of eccentric and concentric trainings in the IL and IK modes. The mechanical characteristics inherent to each training mode suggest specific response of the neuromuscular system and therefore that each mode would induce specific strength gains and muscle and nervous adaptations. The present study would allow the comparison of the specific responses and adaptations of the neuromuscular system induced by these exercise modes in the same conditions. Such a work could be of interest to coaches and clinicians who need to evaluate the work load or to better determine the objective of their training sessions or rehabilitation programs in which eccentric exercise is currently used.

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